CREEP BEHAVIOR AND DURABILITY OF CONCRETE ELEMENTS STRENGTHENED WITH NSM CFRP STRIPS

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ABSTRACT: This paper presents an experimental program aimed to better understand durability and long-term deformational performance of concrete structures strengthened with the near-surface mounted (NSM) technique. The conducted experiments include beam pullout specimens and slabs. Both types of specimens were submitted to sustained loads under the following environmental conditions: (i) placed in the laboratory premises; (ii) immersed in a water tank at 20ºC with 0% of chlorides; (iii) immersed in a water tank at 20ºC with 3.5% of chlorides; (iv) submitted to wet/dry cycles at 20ºC with 3.5% of chlorides. The mid-span vertical deflection of the slabs was continuously monitored, whereas the beam pullout specimens had their loaded end slip monitored. Creep, degradation and their relation with temperature were some of the observations pointed out. The effect of creep is practically negligible in the beam pull out tests and the evolution of the loaded end slip was mainly controlled by the environmental temperature at the lab. Nonetheless, the slabs have a pronounced creep effect, despite it has been mitigated when the slabs were submitted in water. The paper presents the general description of the experimental program and the first results pertaining to sustained loadings until ages up 439 days (current state of the process).

1. Introduction

The near-surface mounted (NSM) strengthening technique using fiber reinforced polymers (FRP) is usually applied in order to increase the load carrying capacity of reinforced concrete (RC) members. Over the last few years, the experimental, numerical and analytical research of NSM FRP reinforcement systems has essentially proven the structural effectiveness of this technique (De Lorenzis and Teng, 2007). Nonetheless, once the NSM is an emerging technique, some critical issues associated to the long-term behavior and durability still need further research.

Currently available data on the effects of creep on bond behavior of NSM CFRP strengthening systems is limited. In fact, published research on creep effects mostly focuses on the structural behavior of strengthened members and on individual components (concrete, steel reinforcement, FRP, adhesive) (Ascione *et al.*, 2008, Costa and Barros, 2012). In concern to durability of this strengthening technique, Derias *et al*. (2008) performed durability tests wherein CFRP NSM strengthened T-beams were simultaneously submitted to high temperatures (+55ºC), high salt concentration (of 15% sodium chloride) and with or without sustained load (around 40% of the loading capacity). The observed results of the all specimens pointed out a decrease on the loading carrying capacity of 40% and 11% when the specimens were strengthened with CFRP materials with external surface rough and smooth, respectively. Therefore, the decrease of loading carrying capacity of beams with sustained load subjected to this severe environmental exposure was not aggravated by the sustained load. The beams exposed to the different environments failed by deboning at the concrete/epoxy interface due to its significant degradation, whereas the control beams failed by the rupture of the NSM FRP materials.

Notwithstanding the fact that these works have involved a limited number of specimens, it was clear that aggressive actions yielded non-negligible decreases in the ultimate strength, as compared to reference prototypes. In order to contribute and to appraise the long-term behavior and durability of NSM CFRP strips on the flexural strengthening of reinforced concrete elements, an experimental program was carried out and reported in this paper. In the next section the experimental program is outlined in terms of test setups and procedures. Two different scales were used: the mesoscale for the pullout specimens in order to evaluate the bond behavior, and the full scale, for the slab specimens to assess the overall structural behavior. The following environmental and loading actions were studied: water immersion, effect of chlorides, wet-dry cycles and sustained load (creep).

2. Experimental program

2.1. General description

The experimental program is composed of ten strengthened slabs (SL) and ten beam pullout (BP) specimens through five series (S) as shown in Table 1. The series S0 and S1 correspond to the specimens without loading condition (UN – unloaded and with loading condition (REF) in laboratory environment, respectively. In the remaining series (S2 to S4), besides being exposed to an environmental action, the specimens were also submitted to sustained loads. The following three environmental actions were considered: immersion in a water tank at 20ºC with 0% of chlorides (Series S2); immersion in a water tank at 20ºC with 3.5% of chlorides (Series S3); and exposure to wet/dry cycles with water at 20ºC and 3.5% of chlorides (Series S4). Moreover, six concrete cubes, twelve CFRP laminate strips and twelve epoxy specimens were also submitted to the same environmental actions. Half of the specimens were submitted to these actions during 360 days (theoretical), whereas the other half will continue up to 720 days (theoretical). At the end of each aging test, the specimens were monotonically tested up to failure. The code names given to the test series consist on alphanumeric characters separated by underscores (see Table 1). The first string indicates the specimen type (BP and SL). The second string defines the environmental action (REF, PW, CW and WD). Finally, the last string indicates the number of days that the specimens were submitted to the environmental action.

Table 1 – Experimental program.

Series	***Environmental action***	***Beam pullout specimens***	***Slab specimens***
S0	Lab environment (21ºC +/- 10ºC)	BP_UN360 BP_UN720	SL_UN360 SL_UN720*
S1	Lab environment (21ºC +/- 10ºC)	BP_REF360 BP_REF720	SL_REF360 SL_REF720
S2	Prototypes immersed in pure water at 20ºC	BP_PW360 BP_PW720	SL_PW360 SL_PW720
S3	Prototypes immersed in water at 20ºC with 3.5% of chlorides	BP_CW360 BP_CW720	SL_CW360 SL_CW720
S4	Prototypes submitted to wet/dry cycles with water at 20ºC with 3.5% of chlorides	BP_WD360 BP_WD720	SL_WD360 SL_WD720

In order to assist a better understanding of the experimental program, Fig. 1 depicts its mains steps. The steps time included corresponds to the beginning of the first event. It is possible to identify all the steps of this experimental program until now. The strengthening of the all specimens was performed in the lab with an average temperature value of about 25ºC and 42% of relative humidity (RH). After that the specimens were kept in lab environment until the beginning of the aging tests. More information related to the preparation of the specimens is available elsewhere Sena-Cruz *et al*. (2013). In order to define the value of the sustained load to be applied to the specimens, reference monotonic tests up to the failure of companion similar specimens were performed prior to the environmental actions submission. The strengthened slab (STR) and the bending pullout (BP) specimens achieved a maximum load of 31.63 kN and 24.25 kN, respectively. At this moment the average compressive strength in cylinders was 49.66 MPa, with a coefficient of variation (CoV) of 3.19%. The total load applied in each slab for creep testing was 10 kN, which corresponds approximately to 1/3 of its corresponding ultimate load. Regarding to the BP tests, the total load for creep testing was approximately 7 kN. This load was defined in order to submit the CFRP to a similar strain level as that of the CFRP of the slab creep tests. The sustained load was applied in two distinct steps (L1 and L2) due technical difficulties addressed in Sena-Cruz *et al*. (2013). In the first load step (L1), at about 40% and 24%, of the slabs and BPT total load, was applied, respectively. Then, in the load step L2, the necessary adjustments were made in order to reach the pre-defined load level for creep testing. At 402 days of age, the specimens were submitted to the environmental actions previously mentioned. The aging tests had a total duration of 241 days.

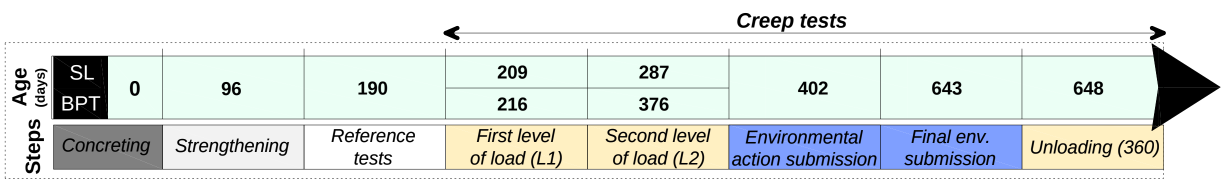

Fig. 1 – Steps of the experimental program.

2.2. Specimens and test configuration

Fig. 2a and 2b show the geometry and test configuration adopted for the beam pullout specimens. The specimen is composed by two concrete blocks (A and B) of equal size, each one with 150×200×385 mm^3 of dimension. In each block, 5 stirrups composed by 6 mm diameter rebars (Ø6) were used to avoid shear failure. Additionally, these blocks were longitudinally strengthened with 2Ø8 at the bottom and 2Ø8 at the top. The concrete cover was 20 mm.

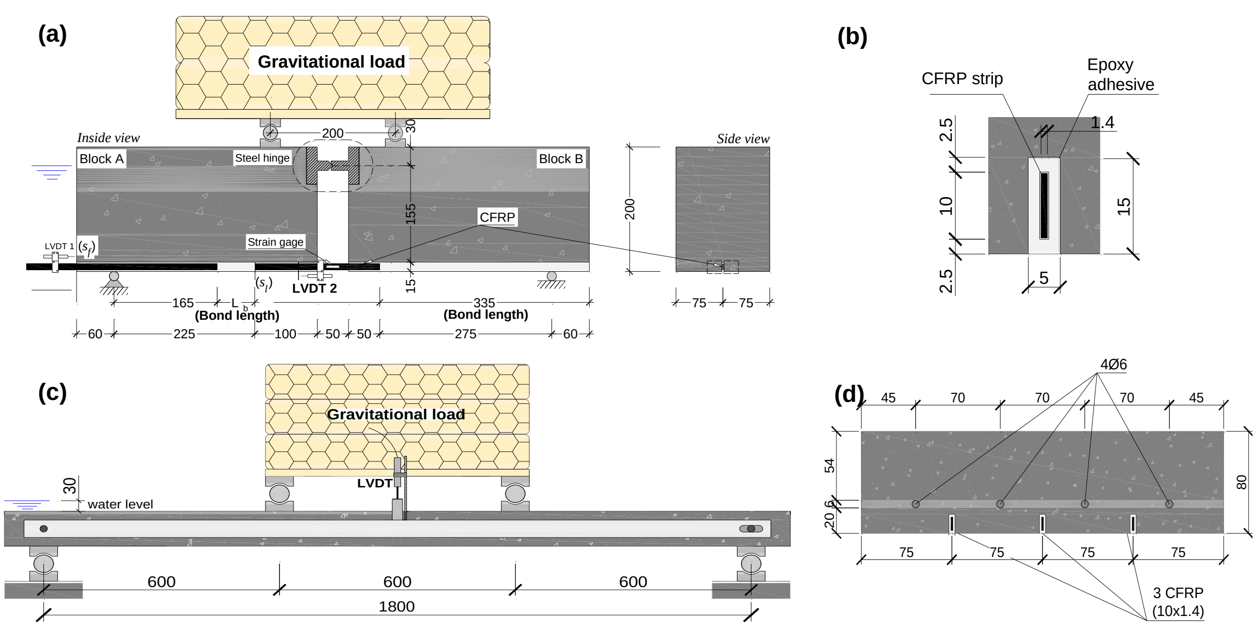

Fig. 2 – Tests configuration: (a) beam pullout specimen; (b) geometry details of the strengthening; (c) slab specimen; (d) slab cross-section (dimensions in mm).

The blocks are interconnected by a steel hinge located at mid-span in the top part, and also by the CFRP laminate strip (1.4 mm thick and 10 mm wide) fixed at the bottom. The bond test region was located in the bottom part of block A, with the fixed bonded length (L_b) equal to 60 mm. The bond length started at 100 mm distance from the extremity of the block to avoid premature splitting failure in the concrete ahead the loaded-end. On block B, the bond length was higher (335 mm) as this was not the side of the specimen to be tested. During the creep aging tests, the strains through the strain gauge glued on the CFRP surface placed at the mid-span of the specimen, the displacements through the LVDT2 were measured. The LVDT2 is used to assess the slip at the loaded end, s_l.

Fig. 2c and 2d show the creep test configuration as well as the cross-section geometry of the slabs, respectively. The slabs were 2000 mm long, 300 mm wide and 80 mm thick. The longitudinal reinforcement was composed by 4Ø6. The flexural strengthening solution was composed by 3 NSM CFRP (10x1.4 mm^2) laminate strips. In this experimental study, a four-point bending test configuration was adopted. The mid-span deflection of each slab submitted to sustained loading was monitored with a LVDT and a mechanical dial gage at opposite lateral face (see Fig. 2c). Regarding to the monotonic tests up to the failure, the details about tests configuration are available in Sena-Cruz *et al*. (2013).

3. Results and discussion

3.1. Pullout specimens

As previously mentioned, the total sustained load applied to the beam pullout specimens was approximately 7 kN. The evolution of the loaded end slip for these specimens along time is presented in Fig. 3. These charts also include the evolution of temperature during the creep tests, which had a clear effect on the measured slip. In fact Fig. 3 shows similar evolution for the temperature and the slip. When the first load step (L1) was applied (approximately 1.7 kN) an instantaneous slip less than 0.1 mm was occurred. This value is coherent with the slip obtained in monotonic test (Sena-Cruz *et al.*, 2013). The reference specimens, represented by green line, installed outside of the tanks (laboratory environment), seem to be less affected by this effect. The reason for this smaller effect of temperature may be related to local microclimatic conditions associated to the placement of these specimens within the laboratory.

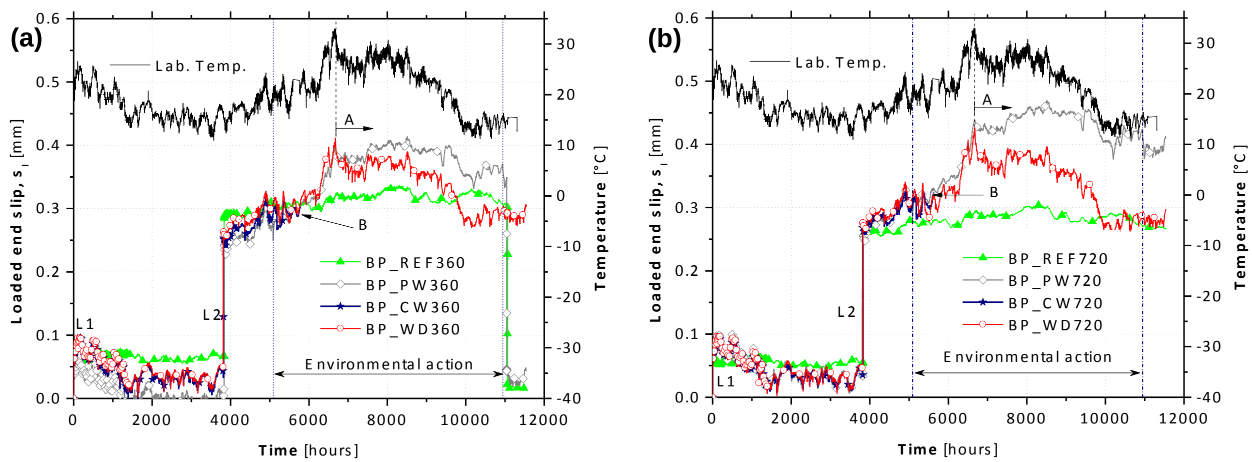

Fig. 3 – Loaded end slip versus time of the beam pullout tests: (a) 360 series; (b) 720 series.

After application of the second load step (L2~5.3 kN), it is clear that the evolution of the slip is also governed by the temperature, and the creep effect is practically negligible. Comparing the creep results of series S3 (PW) and S4 (WD) before the point A (see Fig. 3a and b), the behavior of both series is similar. However, after point A, they exhibit a slight difference in terms of slip evolution. This difference might be related to a slight difference between the temperature of pure water and surrounding environment.

During the creep tests some of the LVDTs were damaged by the environmental action (chlorides). For this reason from point B in specimens BP_CW360 and BP_CW720 the s_l could not be registered. Up to the end of the loading phase the maximum slip observed was 0.47 mm for specimen immersed in pure water (BP_PW720). After the unloading phase, all the unloaded specimens reached a full recovery of the total slip. The residual slip was approximately 0.02 mm, which corresponds to 4.83% of the maximum slip observed in the specimens with unloading phase (see Fig. 3a).

3.2. Slab specimens

For each of the tested slabs, Fig. 4 shows the results of the ongoing creep tests in terms of the evolution of deflection at midspan over the time. In the same figure some events were marked, namely: I – the beginning of the creep test with total sustained load applied; II – the moment when the specimens were submitted to the environmental conditions; III and IV – instants immediately before and after unloading, respectively; V – the current state. Temperature evolution of laboratory environment is also depicted in the Fig. 4. The first load step (L1) caused an instantaneous deflection of approximately 2 mm. The magnitude of this deflection is in agreement with the results obtained in the monotonic test of slab STR carried out previously (Sena-Cruz *et al.*, 2013). The maximum difference of the applied load for distinct slabs during step L1 was limited to 0.7 kN, thus explaining the slightly distinct deflections observed for each slab. During 78 days, the deflection of mid-span due the step L1, changed from 2.0 mm to 3.2 mm (a variation of about 60%) due the creep effect. After applying the creep load of step L2 (event I), the total average deflection at mid-span was about 14 mm (CoV=3.6%), against the 11.5 mm obtained in the monotonic test of STR slab for the same level of loading. More details up to this stage of creep test can be found in Sena-Cruz *et al*. (2013).

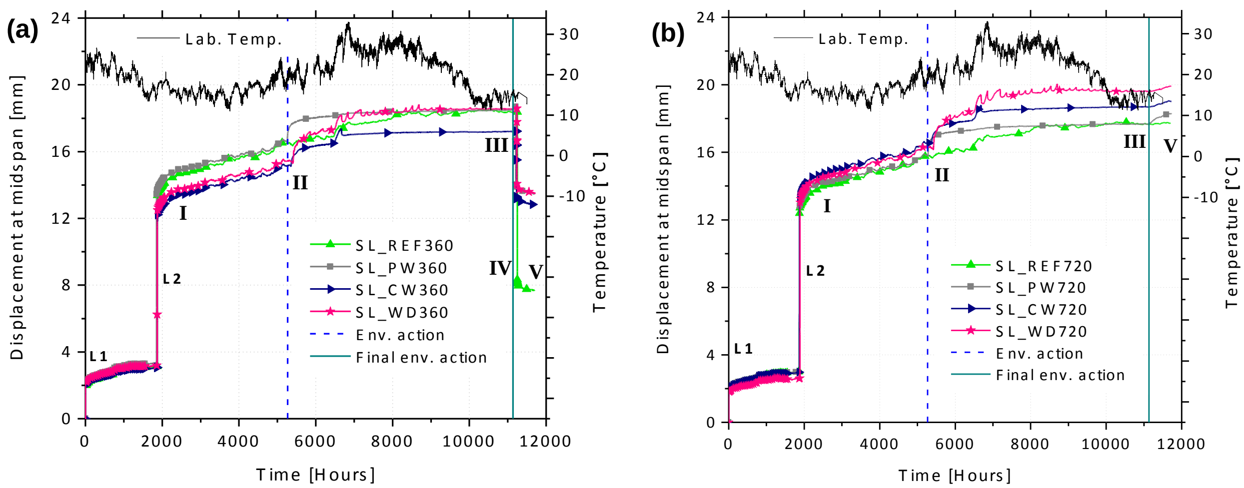

Fig. 4 – Displacement at midspan versus time of the slab tests: (a) 360 series; (b) 720 series.

By analyzing the evolution of midspan deflection for instants I and II due to creep phenomena, in which all the slabs were submitted to identical load conditions, it can be observed that the creep deflection increased about 1.9 mm (CoV=6.49%), corresponding to a variation of deformation of approximately 13.2% (CoV=4.41%) during 220 days. Nevertheless, at event I of Fig. 4a, slight differences can be observed in the displacement at midspan between SL_REF360/PW360 and SL_CW360/WD360 slabs (~0.7 mm). When the specimens were submitted to the environmental action, an almost “instantaneous” deformation increase (took place during approximately 4 days) of about 1.1 mm was observed, on average. This phenomena could be related to a possible combination of the following reasons: (i) the difference of temperature between water and slab (thermal shock effect); (ii) water absorption by the concrete (porous material), more accurately, the underpressure in the pores caused by capillary action; and, (iii) diffusion of chlorides, in the cases that it is present (Bertolini *et al.*, 2013). Afterwards and up to the unloading stage for 360 series, a clear decrease of creep effect is observed in all the specimens expressed by a lower rate deformation. Nonetheless, creep phenomena were more pronounced in the REF and WD specimens, in which the increase of deformation was about 11%, without accounting to the instantaneous increase due the placement of water in tanks. The slabs of the series PW and CW, showed a lower increase in terms of deflection, of about 5% and 7%, respectively. The explanation of this aspect should be related with the temperature of the water since it was kept approximately constant (between 21°C ±3°C) while the other specimens (REF and WD) were directly subjected to the laboratory temperature.

After unloading, as shown in Fig. 4a, the slab SL_REF360 recovered about 10.3 mm of deformation, which is approximately twice as much of the recovery recorded in the remaining slabs. The elastic deformation (which corresponded approximately to 12 mm for L1 + L2) was almost recovered. This behavior is not observed for the remaining slabs (PW360, CW360 and WD360). Indeed, the drying and the degradation may have delayed the recovering of deformation.

4. Conclusions

This work focused on the durability and the long-term behavior of strengthened elements with CFRP NSM technique, with description of an extensive long term experimental program. Even though this research is still under way, it is already possible to point out some preliminary conclusions. From the obtained results on beam pullout tests, it can be observed that the effect of creep is practically negligible. The evolution of the loaded end slip was mainly controlled by the environmental temperature at the lab. When the beam pullout results are compared to those of the slabs, the temperature effect is more pronounced in the former, since the CFRP laminates in slabs are totally surrounded by the adhesive and concrete, reducing the temperature exposing. Regarding to the slabs, a pronounced creep effect was observed, which it was mitigated when the slabs were submersed in water. In the unloading phase, the total elastic deformation was practically recovered by the reference slab, whereas the slabs submitted to the environment action only recovered about half of its elastic deformation. Nevertheless, the deformation recovery is still observable for all the slabs.

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